

# Thermal Pollution Consequences of the Implementation of the President's Energy Message on Increased Coal Utilization

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The thermal consequences of coal utilization are most meaningfully assessed in comparison with the form of power generation replaced by coal which is most likely nuclear. The different effects are influenced by siting decisions and the intrinsic thermal efficiencies of the two fuel systems. Nuclear power plants discharge 50% more waste heat to the atmosphere through cooling towers or to a water body than coal-fired plants. Coal-fired plants require about  $\frac{2}{3}$  as much water as nuclear power plants.

Nearly every property of water is affected nonlinearly by temperature, and biological effects may amplify these changes because protein denaturation takes place more rapidly above 30°C and these high temperatures affect bactericidal and viricidal activity of chlorine compounds. Usually algal populations change from a dominance of diatoms and green algae to dominance by blue-green algae. All organisms experience elevated metabolic rates at higher temperatures which may affect total energy needs, foraging ability, reproduction, migration and susceptibility to disease.

Intake structures inevitably draw many organisms into the cooling system of a power plant, but the number and kind are influenced by its location, configuration, and mode of operation. Use of water recirculation systems reduces water use and with it, the number of organisms entrained. Mechanical damage in the cooling system to small organisms is generally low, but fish and their larvae and eggs may be seriously damaged.

Discharge effects may also be severe but are generally local. The near field, where there are strong shear velocities and rapid temperature changes are particularly stressful to fish, and stringent limitations on the timing and strength of discharges may be required to reduce these stresses to nondamaging levels.

Off-stream cooling systems may increase cloudiness, ground fog, precipitation, temperature and local winds, but these effects generally extend no further than 1000 m even in winter.

There is considerable potential for using condenser cooling water for agricultural and aquacultural purposes such as irrigation, frost protection, undersoil heating, greenhouse heating and climate control. However, over the next few decades little of this waste heat is likely to be used creatively.

The thermal consequences of implementing NEP are locally serious but do not pose regional problems. Creative use of the waste heat for aquaculture, agriculture, cogeneration, and power for energy intensive industries can be a powerful means of mitigating undesirable effects.

## Introduction

There are no direct human health effects from the discharge of heated waters. There are however, health effects induced by the use of control technology to reduce the environmental effects of heated water discharged. The environmental effects of thermal discharges due to increased coal utilization will be in large part determined by the fuel that it displaces. In this instance it is clear that the fuel

displaced for new sources is uranium, as practically no new gas or oil fired stationary power plants will be permitted. However, coal will replace oil and gas in some existing utility power plants. The thermal pollution impact of this replacement is negligible. Though the total usage of coal for electric power generation for the year 2000 will decrease under the National Energy Plan (NEP), in comparison to previously projected growth due to conservation, the percent of electricity generated by coal under the NEP will rise from 40.8% to 44.8%. The major effects of this increased use of coal in comparison to a linear reduction in use of all fuels will be due to the

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different siting possibilities and thermal efficiencies of the two dominant fuel systems, coal and nuclear. These choices will effect total water requirements, consumptive water requirements, biota entrainment and impingement, size of the thermal plume, climatological effect, size of the cloud shadow, etc. Coal fired plants may be located at the mine, or near the load center. There is no incentive to locate nuclear power plants at the mine because the fuel requirements are so modest, 30 tons per year per 1000 MW<sub>e</sub> plant in comparison to 2.3 million tons per year for an equivalent coal plant. The size of nuclear power plant components, particularly the pressure vessel, make it desirable to locate the plant so that barge transportation is possible. Finally, nuclear power plant siting criteria are different from coal power plant criteria with respect to population density and seismic probabilities. Nuclear power plants then tend to be more remotely located from population and load centers than do coal fired plants. If location on a major waterway is given special weight in determining the location of a nuclear power plant, then the location would more likely be suitable for once through condenser cooling than would a coal fired plant. However, coal-fired plants ordinarily will have thermal efficiencies of approximately 40%, while light water reactors will have thermal efficiencies of only 32%. Since both lose approximately 5% of their energy within the building, and coal fired plants lose approximately 10% of their energy up the stack, nuclear power plants discharge 50% more waste heat to the atmosphere through cooling towers or initially, to the water body. In general, if sufficient water for cooling purposes, (makeup water), is available, water does not play a major role in site selection.

In most environmental problems the effects are site-specific. The effects will be determined by the size of the units, the size of the plant, and the size and flow rate of the receiving body of water. The effects will also be dependent upon the topography, climate, season, wind speed and direction and the local biota.

The effect of the total heat rejection rate on the

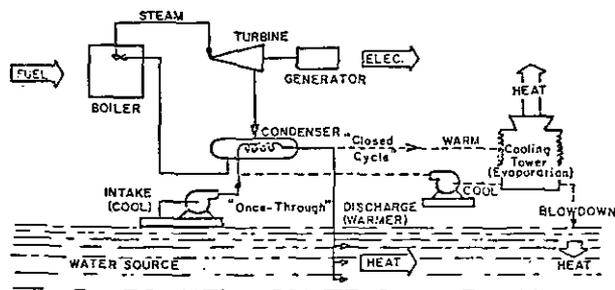


FIGURE 1. Typical water circulation systems.

global temperature has not been calculated but to the extent that coal replaces uranium as a fuel then there is a net reduction in the heat rejected to the atmosphere and a decrease in the rise in the earth's temperature.

A schematic of a typical closed cycle system where the condenser cooling water is recirculated and the open cycle system where the condenser cooling water is discharged directly into the water body is shown in Figure 1.

## Legal Constraints

Heat discharged into water is specifically identified as a pollutant by Section 502(5) of the Federal Water Pollution Control Act Amendments of 1972 (FWPCA) (1). Heated water discharges to surface waters are primarily due to the cooling of industrial processes and steam condensation and the subsequent release to a water body with this additional heat load. The steam electric power industry is by far the largest discharger of heated waters. In 1968, 80% of the total water used for industrial cooling was in the generation of electric power for resale (2). The FWPCA in Section 316 (a) provides for less stringent effluent limitations than those prescribed under Sections 301 or 306 for the control of the thermal component of any discharge. The owner or operator of a point source must demonstrate that less stringent limitations will "... assure the protection and propagation of a balanced, indigenous population of shellfish, fish and wildlife in and on the body of water into which the discharge is to be made (1).

The Administrator of the EPA has published "final" effluent limitations and guidelines for the steam electric power generating category in the Federal Register of October 8, 1974 (3). These are shown in Table 1. The technological basis for attaining these objectives was closed cycle evaporative cooling. Mechanical draft wet towers were the basis for comparison.

Amendments to the final limitation guidelines were proposed in the March 26, 1976 Federal Register which would allow the above categories to discharge heat without limitations to on-stream "recirculating cooling water bodies" (4). These amendments would have the effect of allowing construction of new on-stream cooling lakes and allowing the discharge of heat by new sources on existing lakes, provided such lakes qualify as recirculating cooling water bodies. In addition, in a February, 1975 Memorandum, EPA indicated that 316(b) authorizes regulation of the capacity of cooling water intake structures. Hence, "if limitations on intake structure capacity represent the best available technology for minimizing adverse environmental ef-

Table 1. Final effluent limitations from October 8, 1974 Federal Register

	Type of unit		
	Base Load	Cycling	Peaking
Capacity factor (%)	>60	<60;>20	<20
BPCTCA Effluent limitation on heat	No limitation	No limitation	No limitation
BATEA Effluent limitation on heat	Cold side blowdown only <sup>a</sup>	Cold side blowdown only <sup>a</sup>	Cold side blowdown only <sup>a</sup>
Date Required	July 1, 1981 <sup>b</sup> for all units that: (a) Have net generating capacity (NGC) $\geq$ 25MW or are part of a system with NGC >150MW (b) Have NGC $\geq$ 500MW and were completed after 1/1/70 (c) Have NGC <500MW and were completed after 1/1/74	Same as for base load <sup>c</sup>	Same as for base load <sup>c</sup>

<sup>a</sup>Exceptions to this limitation: (i) hot side blowdown is allowed if the recirculating cooling system was completed or under construction prior to October 4, 1974; (ii) heat may be discharged where a cooling pond or cooling lake was completed or under construction as of October 4, 1974; (iii) no limitations if no other alternative recirculating cooling system is practicable and sufficient land for mechanical draft evaporative cooling towers is not available or dissolved solids in blowdown >30,000 mg/l. and <150 m of owned land downwind of all practicable locations for mechanical draft cooling towers; (iv) no limitation where no alternative recirculating cooling water system is practicable and plume from cooling tower would cause substantial hazard to commercial aviation as certified by FAA.

<sup>b</sup>If system reliability would be seriously impacted by compliance by this date: (i)  $\geq$  50% of affected generating capacity must comply by July 1, 1981; (ii)  $\geq$  80% of affected generating capacity must comply by July 1, 1982; (iii) total compliance by July 1, 1983.

<sup>c</sup>The final regulations have no direct subcategorization based on capacity factors, instead it is based on size and age. The age subcategory is viewed as effectively including capacity factor considerations. (See text for description of final subcategorization.)

fects, they may be imposed, in a proper case, despite the fact that recirculating cooling systems would not be required to insure that discharges of cooling water met applicable thermal standards."

The regulations promulgating effluent limitations guidelines and new source performance standards for steam electric power plants were challenged by 78 petitioners who own and operate over 50% of the country's electric generating capacity affected by the challenged regulations. The basic contention of the electric utility industry was that EPA promulgated inflexible regulations which when fully implemented will impose enormous costs, will waste valuable energy resources, and will result in little, if any, environmental benefits.

The United States Court of Appeals, Fourth Circuit on July 16, 1976 in *United Water Act Group v. Russell E. Train* set aside the majority of the regulations and remanded them to EPA for further consideration and directed EPA to include a variance provision for new sources in accordance with their opinion (5). A new set of regulations and variances has not been released. Consequently the degree of control and the effects thereof cannot be estimated on unknown regulations. This analysis, therefore, will be based on the published regulations and the February, 1975 memorandum.

In the past EPA had estimated that 80% of existing power plants and 50% of new power plants might qualify for exemptions under Section 316(a). However, industry sources dispute these numbers and believe that a smaller percentage of exemptions will be granted. The experience as of February 28, 1977 has been that four of 80 316(a) demonstrations have been denied (6). If this ratio holds generally, then 316(b) may require more offstream cooling to decrease the biota exposed to the stress of flowing through the cooling system than do effluent limitations.

## Economic Effects

The economic penalty due to the installation of off stream cooling will be due to the capital costs of the cooling equipment plus land acquisition and costs of auxiliary equipment such as pumps, motors, control systems, etc.; the cost for operation and maintenance of towers or spray modules, or cooling ponds which includes the energy costs to operate pumps and fans (if required); and additional costs of generation of the power due to a decrease in the plant heat rate. (The number of BTU's required to produce 1 kw hr of electricity).

EPA's estimates of the costs of meeting the new

**Table 2. Summary of the total cost of the effluent limitation guidelines.**

Impact	Level I 1977 standards		Level II 1983 standards <sup>a</sup>	
	Before exemptions	After exemptions	Before exemptions	After exemptions
<b>Financial effects</b>				
Capital investment (billion \$)	9.4	3.8	28.5	14.5
Increase over baseline (%)	10.0	4.0	7.8	4.0
<b>Price effects</b>				
Increased revenues per year (billions)	1.4	1.0	6.2	3.7
Price increase in mills/kWhr	0.5	0.4	1.7	1.0
Price increase (% cost to final user)	2.4	1.7	5.5	3.3
<b>Capacity penalty</b>				
Total capacity penalty <sup>b</sup>	2,800	1,700	17,300	5,900
% of national capacity	0.5	0.3	2.2	0.7
<b>Fuel penalty</b>				
Total fuel penalty (million tons coal equivalent) <sup>c</sup>	6	4	38	13
% of national demand for energy	0.15	0.1	0.9	0.4

<sup>a</sup>Figures shown for Level II represent the cumulative effect of 1977 and 1983 standards.

<sup>b</sup>Total replacement capacity needed to run the cooling towers and to compensate for capacity lost due to increased turbine back pressure.

<sup>c</sup>Total increase in demand for nuclear and fossil fuel expressed in million BTU and divided by the average BTU per ton of coal (e.g., 24 million BTU).

source performance standards are shown in Table 2 (7). The estimated busbar electricity cost increases (1977) due to closed cycle cooling rather than open cycle cooling for coal fired plants in mills/kw-hr were 0.13, 0.29, and 0.42 for cooling ponds, mechanical wet and natural draft wet cooling towers respectively (8).

**Table 3. Cooling water requirements for 1000 MWe plant.**

Cooling method and plant type	Intake, ft <sup>3</sup> /sec	Consumed, ft <sup>3</sup> /sec	
		USGS	EPA
Once-through			
Nuclear	2150	18	
Coal	1300		8.2
Mechanical draft wet cooling tower			
Nuclear	43	31	
Coal	25		10.6
Natural draft wet cooling tower			
Nuclear		29	
Coal			10.6
Cooling pond <sup>a</sup>			
Nuclear		21	
Coal			11.2

<sup>a</sup>Not including natural evaporation.

## Water Requirements

Based upon experience in the nuclear energy field as expressed in the environmental impact reports, the U.S. Geological Survey has estimated the consumptive losses for 1000 MWe nuclear plants as shown in Table 3 (9). The estimates are based on the geographic locations where nuclear plants were built or are planned to be built. The losses whether evaporative, radiant or convective, are a function of the climatic conditions that obtain at the site. The losses are also determined by the range (temperature difference between the entering and exiting water), amount of drift, and the cycles of concentration. Cooling ponds, because they are effected by these variables more than towers, show even a wider range of values for water requirements. The water requirements are therefore site specific and the problems they may cause are also site specific. Coal fired plants as indicated earlier require 0.67 times as much water as nuclear power plants. It should be noted that the authors indicate that these values are greater than the evaporative needs for cooling and therefore, are assumed to represent total water losses. Tichenor (8) quotes estimates for Lake Michigan, and they are quite different. They are also shown in Table 3. Obviously, more experimental evidence is necessary to determine the consumptive water losses in various cooling systems. The total water withdrawals for once through cooling systems are the easiest to calculate and to measure.

Water loss by evaporation by the various types of cooling devices varies quite widely. The amounts lost depend upon the specific environmental and plant conditions. Lakes, ponds, rivers, reservoirs and estuaries lose only about 40% of their heat by evaporation. Wet cooling towers lose 75% or more of the heat by evaporation, and dry cooling towers lose no heat by evaporation. The amount of water lost by evaporation is a function of the wet bulb temperature of the air, relative humidity, cloud cover, wind speed, range of cooling, and heat losses by other mechanisms.

The Water Resources Council has carried out a detailed study of water requirements for energy needs. Though the study is not yet complete, it is estimated that over 60% of the additional water consumption requirements between 1975 and 2000 will be used for energy related purposes (10). This includes, in addition, to steam electric generation, coal extraction, gasification, and liquefaction, and oil refinery uses. The impact of this consumptive use is also site-specific.

## Physical, Chemical and Biological Effects of Heated Water

Temperature affects nonlinearly nearly every property of water. Consequently, when heated water is discharged the environmental equilibrium is shifted. With increasing temperature, the density, viscosity, surface tension, and oxygen solubility are decreased (11). With increasing temperature, the vapor pressure, oxygen diffusivity, and the stream reaeration and biological oxidation coefficients are increased. The lower oxygen saturation solubility and the higher biological oxidation rate cause the oxygen demand to peak earlier in time and place and higher, thereby reducing the waste assimilative capacity of the stream. In addition, the higher vapor pressure causes an increase in the evaporation rate which cools the water body faster but may also lead to substantial losses of water.

At temperatures above 30°C, protein denaturation takes place more rapidly. At elevated temperatures there is also a synergistic effect on the bacteriocidal

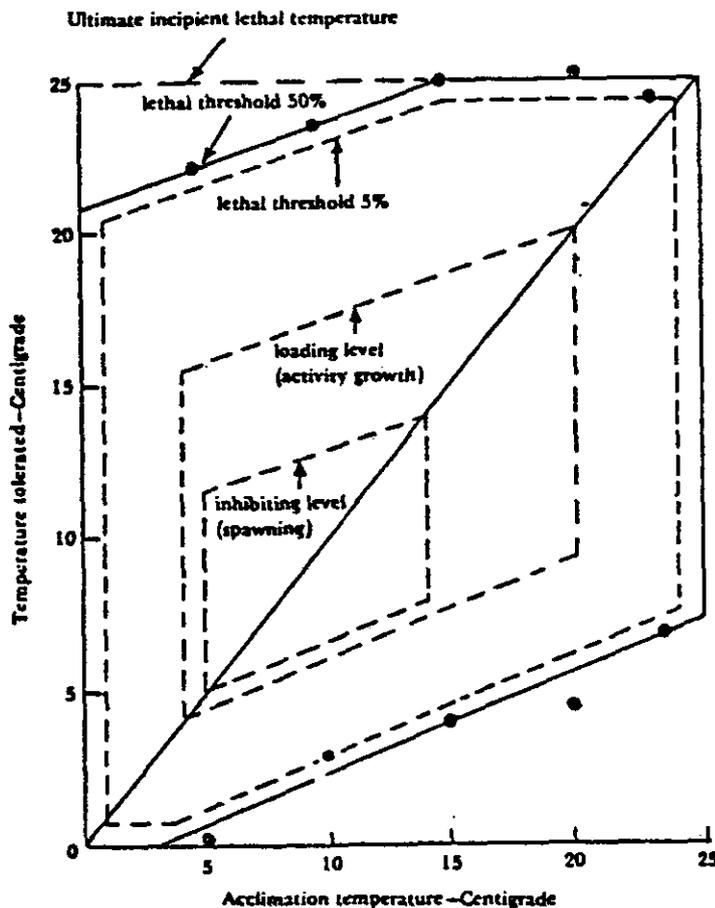


FIGURE 2. Brett's temperature tolerance trapezium for young sockeye salmon.

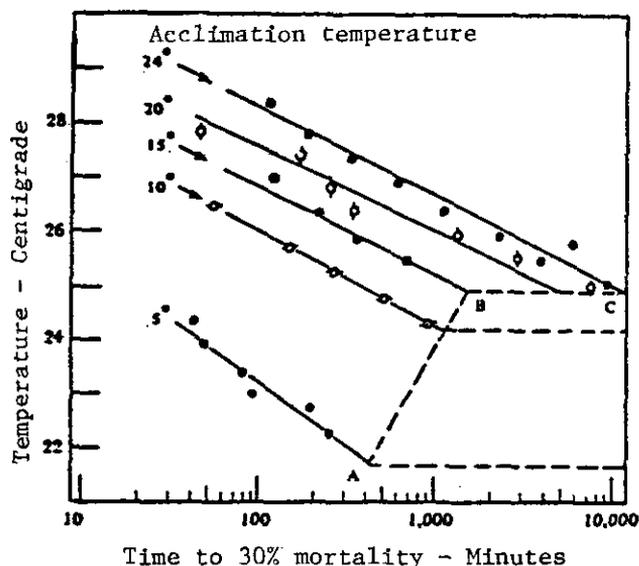


FIGURE 3. Median resistance times to high temperature among young chinook acclimated to temperatures indicated. Line A-B is the incipient lethal temperature and line B-C is the ultimate upper incipient lethal temperature.

and viricidal activity of chlorine compounds. Synergism has also been demonstrated with a number of other compounds.

Temperature effects on aquatic organisms are quite different depending upon the trophic level, species and life cycle stage. Among the more prominent effects are the following. (1) A shift occurs in the population structure of the ecosystem, such as the change in algal populations from diatoms to greens to blue-greens as the temperature rises. (2) Death beyond certain temperature is best illustrated in Brett's tolerance trapezium which relates the effect of acclimation temperature for a life cycle stage to temperature tolerance (12). In addition, the tolerance dose is a nonlinear function of the time exposed to any of the temperatures. Figures 2 and 3 illustrate the effects (13). (3) Sublethal functional responses include increased metabolic activity at higher temperatures which may cause fish to be unable to perceive or capture its food, unable to escape more hardy predators, and unable to tolerate physiochemical environmental changes because they lose their ability to react normally to their environment. Fish respond to temperature in their spawning time and places, their migration and distribution and their rate of feeding and growth. At higher elevations, in general, fish are more susceptible to parasites and diseases.

These effects are easily seen in the vicinity of heated discharges below power plants where a specialized fish population occurs. When the plant is

shut down rapidly, there can be severe thermal stress on the fish resulting in large scale fish kills.

## Biological Effects of Cooling Water Intakes and Discharges

Water and its associated biota is withdrawn from a water source, passes through trash racks and screens, goes through the pumps where it is subjected to mechanical stress and increased pressure, flows through the condenser where it is subjected to thermal shock, and then flows out through a discharge diffuser at high speed to the water source. If a closed cycle system is used, then the water and biota are pumped to the spray nozzles in a cooling tower or spray pond and released at atmospheric conditions and cool toward ambient or wet bulb temperatures. Intermittently or constantly they will be subject to chemical attack from algicides and corrosion inhibitors. At each step the impinged and entrained organisms are subject to abnormal stresses.

### Intake Structures

The location, configuration, and operation of the intake structure can limit the number and type of organisms which are drawn into the cooling system (14). In addition, the total volume of water required, and inferentially the number of organisms, can be dramatically reduced by the use of a water recirculation system. The aquatic organisms usually affected by intake systems are plankton (free floating microscopic plants and animals with limited swimming ability), and nekton (free swimming organisms, i.e., fish). In the egg and larval stages, fish behave more like plankton than nekton. Information on the distribution of plankton in the water body is often poor. A recent study indicates that the structure of the velocity field must first be determined and then the organism movement can be superimposed on that, assuming that the organisms are sufficiently sparse that they do not alter the flow of the water (15). No other mathematical intake models are known to exist.

Nuclear power plants have an additional constraint on intake location in that they must be at a site where "the source of cooling water and/or the ability of the ultimate heat sink to perform adequately under severe hydrometeorological conditions" is not impaired.

### Condenser Cooling Water Systems

A National Academy of Engineering Report (16) has suggested that for once-through cooling systems the transit time in seconds times the temperature rise

(Centigrade) across the condenser should be equal to or less than 2000. For all practical purposes, all entrained multicellular organisms are killed in cooling towers or spray canal cooling systems due to the temperature shock, the long residence time in the cooling system, mechanical abrasion during recirculation in the system and the chemical stress. In cooling ponds and lakes, the survival rate depends upon lake surface area, turnover, winds, dew points, makeup temperature, chemical conditions, etc., and are site specific.

For once-through cooling, the following effects have been observed (17).

**Phytoplankton.** Most studies have employed indirect methods such as primary productivity and chlorophyll a concentration. Photosynthesis in the effluent phytoplankton is stimulated during months when ambient water temperatures are low and inhibited when water temperatures are high. Mechanical damage to phytoplankton appears to be small.

**Zooplankton and Other Crustacea.** The maximum absolute temperature as well as the temperature rise and time of passage affect the mortality rate, which ranges from 1.3 to 6.5%. Mechanical damage appears to vary from 7 to 12% in Lake Michigan power plants.

**Fish Eggs, Larvae and Fry.** Possibly the most serious problem in that mortalities greater than 90% have been reported, dependent again upon absolute temperature, temperature rise, and time exposed to the elevated temperature. Mechanical damage to both zooplankton and fry increases with size of the organism. Almost complete mechanical destruction of fish eggs has also been reported.

Depending upon the percent of total water flow passing through a once through cooling system, and the mortality, reproduction rate and the life span of the organisms, a large percentage of organisms can be destroyed without significant ecological damage. However, entrainment at the cooling system at Indian Point was considered to be such a threat to the survival of the striped bass that cooling towers were mandated.

Butz et al. caution that many questions regarding investigative methods and ecological significance of entrainment damage remain largely unanswered: effect of diet, variations in physiology, behavior and distribution of entrainable organisms on sampling; effect of entrainment on other organisms in aquatic ecosystems such as protozoa, natural bacteria and nanoplankton; effect of sampling, sampling efficiency, and selectivity; delayed effects of entrainment including increased susceptibility to predation losses; effect of selected mortality on entrained organisms and compensatory population response.

If the units are located on estuaries to provide the

amount of water required for once through cooling, they are thereby located in biologically productive area where damages are likely to be more significant.

## Discharge Methods

Comprehensive review of discharge methods (18-20) has been carried out to determine which mathematical model has the greatest predictive utility. The observations by Dunn et al. in their review is equally applicable to all types of models (19).

"It is concluded that, of the models so far compared with prototype data, none has been shown adequate over a wide range of conditions. Moreover, available models were found useful for only *generalized estimates* of plume characteristics; precise predictions are not currently possible."

**Jet Discharges — Near Field.** In this region, momentum dominates diffusive forces and a rapid temperature decrease takes place due to dilution with ambient water. The main mechanisms are jet-induced entrainment due to the large shear velocities between the discharged and ambient flows. It is in this region that the most stressful conditions for fish usually occur. Limits for these stresses have been recommended by the National Academy of Sciences — National Academy of Engineering Committee on Water Quality Criteria (13).

Maximum weekly average temperature should not exceed one-third of the range between the optimum temperature and the ultimate upper incipient lethal temperature of the species.

Maximum weekly average temperature during winter months should not exceed the acclimation temperature (minus 2°C) that raises the lower lethal threshold temperature of such species above the normal ambient water temperatures for that season.

Fish should be exposed to high temperatures for times less than the length of time that 50% of a population will survive temperature above the incipient lethal temperature plus a 2°C safety factor.

Periods for gonad growth and gamete maturation should be preserved.

There should be no temperature differentials that block spawning migrations.

Temperatures at which incubation and spawning can occur should be preserved.

Sharp temperature changes should not be induced in spawning areas.

Timing of reproductive events should not be significantly altered from contemporary conditions.

The normal patterns of gradual temperature change throughout the year are maintained.

Nuisance growths may limit the temperature requirements.

**Far Field — Ambient Turbulent Mixing.** In this region temperatures are reduced by radiant,

evaporative, and convective losses to the atmosphere. The dominant method of mixing is ambient turbulence. Stress to organisms in this region is low. The region is important because if the heat is not dissipated by time it reaches the next downstream user, the heat injected at that point is additive. The temperature as one proceeds downstream could be increased in this fashion.

Mature fish ordinarily avoid lethal temperatures but if trapped can suffer a thermal death. Younger fish may not be so mobile and may be killed in the near field if the water currents do not move them. Fish appear to be more sensitive to cold shocks and have been killed by sudden drops in temperature after plant shutdown. Thermal discharges into spawning areas may kill eggs and fry in that area plus some adults who spawn there.

Fish in thermal discharges may also get the "bends" when the water in which they are swimming is already saturated. The disease has been noted in a dozen species of warm water fish in the thermal discharge, when the nitrogen gas in their bodies becomes super saturated.

## Conclusion

These biological effects are diminished for coal-fired plants in comparison to nuclear powered plants because coal-fired plants withdraw and discharge only about two-thirds of the water required for nuclear plants for the same water temperature rise.

**Table 4. Capital costs of off-stream cooling devices for fossil-fueled systems.**

System	Capital cost, \$/kw electrical
Once through	5-8 <sup>a</sup>
Natural draft wet cooling towers	14-21 <sup>a</sup>
Mechanical draft wet cooling towers	13-18 <sup>a</sup> (14) <sup>b</sup>
Cooling ponds	11-16 <sup>a</sup>
Spray canals	13 <sup>c</sup>
Dry towers	58 <sup>b</sup>

<sup>a</sup>Data of Tichenor (8), 1977 dollars.

<sup>b</sup>Data of Larinoff (21), 1974 dollars.

<sup>c</sup>Data of Hughes (22), 1972 dollars (Quad Cities only).

## Off-Stream Cooling Systems

It is necessary to condense the turbine exhaust steam to pump it back to the boiler. In general, water is used to cool the steam, through in water short areas air can also be used to cool the steam. Usually, the simplest and least expensive system is once through water cooling. The water from a river, lake, reservoir, estuary, ocean, etc. is pumped through trash racks and screens to the condenser and discharged back to the water body. The excess heat is transferred to the atmosphere from the water body by evaporation, convection and radiation.

More complex systems are the off-stream cooling devices, e.g. cooling ponds, spray ponds and canals, wet and dry, and mechanical and natural draft towers. The cooling water is recycled through the cooling device after flowing through the condenser and only a small fraction of the flow in a water cooled system is lost by drift (water droplets), evaporation, and by blowdown (bleed to maintain the concentrations of dissolved substances at acceptable levels). Various combinations of the above are possible such as wet-dry systems to conserve water and to reduce fogging and icing and open cycle cooling where only a portion of the waste heat is dissipated by the off stream cooling device.

The capital costs of the off stream systems are indicated in Table 4 (8, 21, 22). The Tichenor costs are average costs whereas the Larinoff costs are for Middletown USA, and the Hughes costs are for the Quad Cities Plant. The costs have not been put on the same time basis. In addition, for any specific site the costs could be very different. The Quad Cities costs, for example, are for a system which has a capacity of 62.5% or less about half the time, 37.5% or less about 17% of the time and less than 25% of capacity in the most adverse hot weather conditions. The unique installation of 168 miles of cooling canals (3850 acres of water surface) at the Turkey Point Power Plant (846 MW fuel oil and 1456 MW nuclear) cost about \$36.6 million. Operation, maintenance, and monitoring costs are about \$1 million per year and energy costs are about \$1.5 million.<sup>23</sup>

In Table 4, the costs of operation and maintenance are not given nor is the increase in heat rate taken into account. Recycle cooling systems usually have

**Table 5. Losses due to towers.**

	Capability losses (%)		Energy losses, %	
	Average	Range	Average	Range
Mechanical draft wet cooling towers	2.77	0.09-3.75	2.91	0.09-5.60
Natural draft wet cooling towers	3.82	1.67-3.00	4.62	1.64-11.62

Table 6. Atmospheric pollutants due to capacity loss of 100 MW<sub>e</sub>.<sup>a</sup>

Pollutant type	Pollutants, lb/day
Particulates	144,000
Sulfur oxides	68,400
Carbon monoxide	900
Carbon dioxide	6,600,000
Hydrocarbons	270
Nitrogen oxides	16,200
Aldehydes	4.5

<sup>a</sup>Without control equipment.

water temperatures higher than once through cooling systems since the wet cooling towers are limited to temperatures less than the wet bulb temperature and the dry cooling systems are limited to less than dry bulb temperature (by the so-called "approach" which usually ranges from 10 to 25°F). Consequently, the temperature to which the condensed steam can be cooled is higher than that in water bodies. This higher return temperature then induces a lower thermal efficiency in the system.

Estimates of the capability and energy losses are given in Table 5 (24).

The costs and losses are exemplified by the Browns Ferry cooling tower system where, in 1971 dollars, the capital costs were \$35 million, capacity loss costs, \$5.5 million, and the present worth of operation and maintenance, \$18.7 million (25). For the 3456 MW plant the power required for the cooling tower life pumps, fans and peripheral equipment are 56 MW for normal operation and an additional loss of 35 MW due to heat rate increase or 1.6% capacity loss and 1% energy loss (26).

The energy losses caused by the use of off-stream cooling systems will have to be made up. For the Browns Ferry System, this is approximately 100 MW. If coal generation is used, then increased atmospheric discharges of pollutants will result. If the coal has 10% ash content and 2% sulfur content, the discharges excluding natural radioactivity and trace metals would be as shown in Table 6 (27).

Some chemical problems associated with cooling towers are: delignification (binding agent for the cellulose) caused by the use of oxidizing biocides, such as chlorine and excessive bicarbonate alkalinity; biological growth, which can clog the nozzles and foul the heat exchange equipment; corrosion of the metal components; general fouling by silt, clay, oil, metal oxides, calcium, magnesium salts, organics, and other chemical products, which can cause reduced heat transfer and soiling or oxides on surfaces. Extensive chemical treatment to alleviate these problems is required. In addition the blow-down may have to be treated to meet effluent guidelines under S423.13 and S423.15 of the regulations.

Noise effects of cooling towers tend to be large especially for mechanical draft towers where large fans are required to move large volumes of air. The noise problem would tend to be greater in areas with larger populations in the vicinity of the cooling towers. In addition, cooling towers are imposing structures which may dominate the landscape. Their presence may be considered aesthetically displeasing.

The costs and energy losses for coal-fired plants would be about two-thirds of those for a nuclear fueled plant because of the better thermal efficiencies of coal-fired plants.

## Atmospheric Effects of Off-Stream Cooling Systems

Observed environmental effects of off-stream cooling systems (28) include increases in cloudiness, precipitation, temperature and ground fog, sun shading by visible plumes, drift deposition with increased fallout of herbicides and algicides, interaction with chemical plumes, interference with aircraft, and high winds. These are strongly effected by ambient wind speeds, relative humidities, heat rejection rates, ambient temperature gradient, tower exit conditions, etc. and show strong seasonal variations.

Hanna (28) concludes that atmospheric effects due to waste heat releases from cooling towers and ponds are generally minor from current power production facilities (approximately 3000 MW) but that more serious effects can be expected if large energy centers (10,000 MW and up) are built. Though scores of mathematical models are available for estimating most of these effects there are very few good sets of data to test the models.

Up to 50% of the heat released from cooling ponds and up to 90% of the heat carried from cooling towers is in the form of latent heat (vaporized water). When the water is condensed into clouds then, the sun's rays can be shaded and enhance mildewing of painted surfaces or increases in fungi on crops. The average visible plume length for current energy outputs range from about 250 m to 500 m in the summer and from 500 to 1000 m in the winter. Cumulus or stratus clouds have been observed up to 50 km downwind of the power plant during very humid environmental conditions which can occur from 10-30% of the time depending upon location. One set of model calculations indicates that shadowing at nearby villages due to the power plants is about 2-5 min/m day.

Hanna has also concluded that in power plant parks, of up to 50,000 MW<sub>e</sub> where all the heat is released from a disc 300 m in radius, a cloud of 2500

m in height will persist 95% of the time.

Ground fog occurs when the visible plume reaches the ground. The hazard to traffic, particularly if icing occurs, is obvious. Ground fog is common within a few hundred meters of spray ponds and cooling ponds. Ground fog is also common because of downwash within a few hundred meters of mechanical draft cooling towers but ascends at about 500 meters because of its buoyancy. Fog has also been observed on rare occasions from natural draft cooling towers.

The effects of drift deposition are slight if drift eliminators are properly designed so that only 0.001% of the circulating water is lost as drift. If the drift is uniformly spread around the tower, then the chloride deposition from salt water towers is three orders of magnitude less than the natural deposition of chloride 600 m inland from the ocean. Chromium concentration in grass, tobacco and soil downwind from the mechanical draft cooling towers at the Oak Ridge Gaseous Diffusion Plant were significantly above background up to 500 m of the tower.

Cooling tower plumes have been penetrated by research aircraft. Turbulence in the plume is reported as moderate to high with abrupt wind shear of about 5 m/sec at either edge of the plume. No icing of the plane was reported in the plume.

Though fossil-fired power plant stacks are normally higher than adjacent cooling towers, they have less heat output. Consequently, the final plume rise from cooling towers and smoke stacks is about the same, about 500 m. The ratio of acid drops at pH 4 to 5 to neutral drops at pH 6 to 7 increased from 0.05 to 3.0 as relative humidity increased from 50% to 95%. Increased acid rains are indicated.

Visible vortices are occasionally observed at power plant facilities. Very large buoyant plumes, which are more likely at large energy centers (20,000-50,000 MW) can concentrate vorticity and cause waterspouts and other tornado-like vortices. Vortices have been observed in large scale oil-burner experiments and in larger Australian bushfires. At single cooling towers buoyancy dominates and prevents the concentration of vorticity.

Light precipitation has occasionally occurred from large clouds generated from current power plants and snow from plumes has been observed from 5 to 50 km downstream of the plant. Though no significant difference in rainfall rates have been measured around cooling towers in England (where they have been far more common than here) this may be due to the fact that it is difficult in a statistical sense to verify a statistically significant small increase (approximately 5%) in rainfall. Although cooling tower plumes have the energy content to trigger thun-

derstorms, no reports of thunderstorm generation have been reported.

The atmospheric effects of coal-fired plants would be only about two-thirds of the effects from nuclear-fueled plants because only about two-thirds as much waste heat is discharged as latent heat.

## Mitigation Waste Heat Utilization

The Environmental Protection Agency has indicated (30, 31) that the greatest potential for near term (through 1985) use of condenser cooling water (10-40°F above ambient) has been for agricultural and aquacultural purposes. The most attractive agricultural purposes are in irrigation, frost protection, undersoil heating, and greenhouse heating and climate control. Because high cash-value products, flowers and vegetables are involved, greenhouses appear to be the most promising application. In a recent demonstration greenhouse of ½ acre in Minnesota during the coldest winter in 100 years, condenser cooling water provided soil and air heating for the production of roses, snapdragons, tree seedlings, tomatoes and lettuce. Savings were over \$5,000 per acre year in comparison to fuel oil costs. Commercial development is underway.

Agriculture projects that stimulate biological growth, such as catfish production, algae production for animal food, amur production to recycle nutrients from feedlots, and biological waste treatment have shown the most promise. Mariculture, because of the high value of the product, also shows great promise.

Projected demands for electrical energy by the year 2000 indicate that the predicted heat dissipation from electrical power facilities at that time will equal our total energy demand in 1970. Despite that, it can be seen even for the most promising uses in the near term, little of this waste heat will be used and that will not substantially reduce thermal pollution problems.

For the long term (post-2000), cogeneration offers the best hope. Though most common in Europe, few integrated energy facilities have been built in the United States because of incompatibility of utility and manufacturing and residential use systems, financial risk, lack of necessary capital, and lack of long-term planning.

EPA has shifted its attention from these uses of waste heat to nonpower production energy intensive industries where waste heat use or more efficient conversion technologies offer significant environmental benefits.

At Oak Ridge National Laboratory (32), the order of the most attractive use of waste heat was determined to be in order of preference, extensive pond

aquaculture, animal shelters, algal ponds, intensive raceway aquaculture, under-soil heating and greenhouses. Why the rankings are so different from EPA's is not known. Possibly the extent of use of the systems determined EPA's ratings. For example, the waste heat from less than one 1000 MWe power plant would produce enough catfish, trout, salmon and shrimp to satisfy present U.S. demand. Elasticities of demand were not taken into account. The differences show again how critical the assumptions are in any of these projections.

## Conclusions

The effect of the President's plan to increase coal utilization on the thermal pollution problem is dependent upon the fuel that coal displaces and upon the specific location of the new facilities. Coal-fueled power plants discharge to water bodies or off stream cooling systems about two-thirds of the waste heat that nuclear fueled (LWR) power plants discharge. However, coal fired plants may be located at the mine mouth whereas nuclear facilities would not.

Though the law (PL 92-500) defines heat as a pollutant and therefore requires best available technology economically achievable by 1983, heated discharges are allowed an exemption in section 316a. Best available technology is defined in the regulations as closed cycle evaporative cooling. Depending upon the location, the new power plants may qualify for once through cooling if a balanced indigenous population in the water body can be maintained. If such an exemption can be obtained for once through cooling then the effect of increased utilization will be at worst equivalent to what would have otherwise occurred (maintenance of a balanced stream population) or better (only two-thirds of the waste heat discharged for an equivalent power plant).

If, however, no exemption is possible, then off-stream cooling induces some environmental and health costs. If the new coal-burning facility is at the same location as the nuclear facility would have been, then the effect is less except if the capacity and station losses are made up by units burning a different fuel than initially intended. If both replacements for nuclear are coal, then the health comparison between nuclear fuel cycle effluents and coal fuel cycle effluents must be taken into account.

If the new coal-burning facility is located at a different site (e.g., mine mouth) than the nuclear facility it displaces, and therefore requires off-stream cooling to protect the stream population whereas the nuclear unit would not have required off stream cooling, then the effects can be more severe.

The environmental and health problem will then have been converted from an hydrospheric problem to an atmospheric problem where concentrated sources of latent heat could increase slightly cloudiness, precipitation, temperature, fog, sun shading, localized acid rain, localized deposition of herbicides and algicides, and thunderstorms. If the units are concentrated, tornado-like vortices could be created. Off-stream cooling systems cause capacity and energy losses, and these have to be made up. Whether their increase is from the fossil fuel or nuclear fuel cycle, additional capacity induces additional health and environmental effects.

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